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WIND ENERGY DEVELOPMENTS IN THE 20th CENTURY

NEWARK COLLEGE OF ENGINEERING

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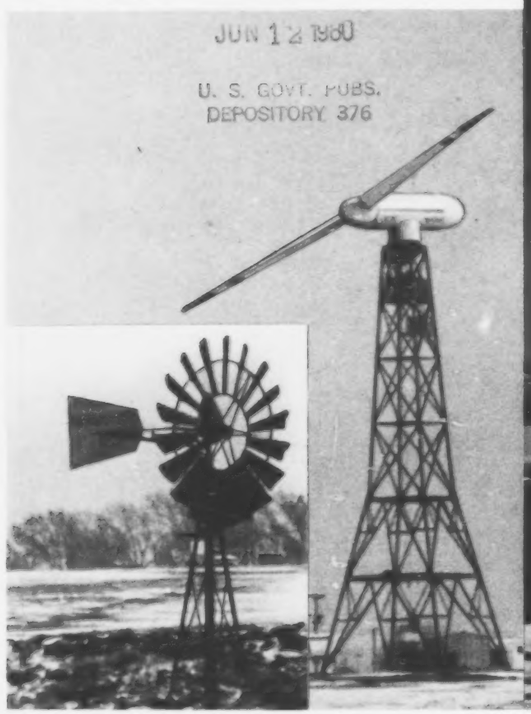

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WIND ENERGY DEVELOPMENTS IN THE 20TH CENTURY

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WIND ENERGY DEVELOPMENTS IN THE 20TH CENTURY

Historically, wind-driven energy conversion devices can be considered as one of man's truly basic machines. Simple vertical-axis wind machines were in existence in Persia several hundred years before the time of Christ (refs. 1,2). These primitive wind machines stayed the same until the 12th century, when almost simultaneously in France and England the horizontal-axis, or Dutch, windmill made its appearance (fig. 1). Dutch settlers brought the windmill to America in the mid-1700's (ref. 3). These windmills typically ground grain and pumped water. Through the years the design of these windmills changed only superficially.

In 1890 the first of the modern windmills for producing electricity was designed, built, and put into service in Denmark (refs. 1,4). By 1908 several hundred wind power stations, each producing from 5 to 25 kilowatts of electricity dotted the Danish landscape. Wind machines played a significant role in rural America until the 1930's, when the Rural Electrification Act (REA) provided cheap electricity to the farmers. The remnants of many of these early wind machines are still visible in various parts of the country. All these machines were relatively small and did not produce much power.

The variation of wind power with wind speed is presented in figure 2. At a wind speed of 13 mph approximately 10 watts of power is contained in each square foot of wind area (where area is taken perpendicular to the wind direction). This represents the theoretical power available. The laws of nature limit the power transmission of ideal propellers to 59.3 percent. Because of the losses associated with a real propeller, gearing, and generator, the power that can actually be obtained from 1 square foot of this 13-mph wind is 3 to 3.5 watts.

In the 20th century the search for power led several countries to attempt to tap this widespread source of "free" energy. For the first time

Figure 1. - Typical Dutch windmill.

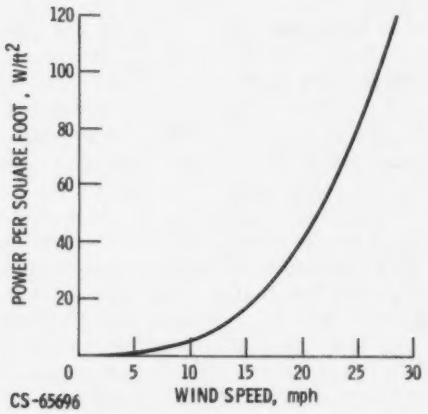

Figure 2. - Power density of wind.

Figure 3. - 100-Kilowatt Russian wind turbine.

comparatively large wind machines were constructed and tested.

One of the first of the large experimental machines was the 100-kilowatt wind turbine that was built in 1931 by the Russians (fig. 3). It was located at Balaclava, near Yalta, on the Black Sea (refs. 5–7). The rotor was 100 feet in diameter and the tower was 100 feet high. Maximum rated power (100 kW) was obtained at wind speeds greater than 24.6 mph. The average wind speed at the site was 15 mph. The rotor drove a 100-kilowatt, 200-volt induction generator that was connected by a 6300-volt line to a 20-megawatt steam power station located in Sevastopol, some 20 miles away. Although this wind machine was very primitive, that is, the blade surface was roofing metal and the main gears were made of wood, one year the plant did achieve an output of 279,000 kilowatt-hours. This gave a power utilization yield (actual power output divided by total possible power output) of 32 percent. The generator and controls were located in the housing on top of the tower. Regulation was accomplished by pitch control of the blade. The wind thrust was absorbed by the inclined strut. The ground portion of this strut rested on a carriage that sat on a circular track. The carriage was automatically driven to keep the rotor facing into the wind. In addition to this machine, many smaller machines have been installed in Russia to supply power to agricultural communities.

The largest wind machine until recently (1250 kW) was started in 1934 when an engineer, Palmer C. Putnam, began to consider wind-driven generators for reducing the cost of electricity at his Cape Cod home (refs. 5, 8–10). In 1939 Putnam presented his ideas and the results of his preliminary work to the S. Morgan Smith Co. of York, Pa. The company agreed to fund a wind energy project, and the Smith-Putnam wind turbine experiment was born. The wind turbine was to be connected to the existing system of the Central Vermont Public Service Corp. Out of some 50 Vermont sites considered, a 2000-foot hill, Grandpa's Knob, located in Rutland, was selected. A number of engineers from several universities participated in the project. On August 29, 1941, less than 2 years after the original meeting, the blades were rotated for the first time.

The Smith-Putnam machine (fig. 4) was physically the largest wind machine ever built and tested. The tower was 110 feet high; the rotor was 175 feet in diameter and had an 11-foot, 4-inch chord. Each blade weighed 8 tons and consisted of stainless-steel ribs covered by a stainless-steel skin. The blade pitch was adjustable so that a constant rotor speed of 28.7 rpm could be maintained. This rotational speed was maintained in wind speeds as high as 70 to 75 mph. At higher wind speeds the blades were feathered and the machine was brought to a stop. The rotor turned an alternating-current synchronous generator that produced 1250 kilowatts

Figure 4. - 1250-Kilowatt Smith-Putnam wind turbine.

of power at wind speeds greater than 30 mph. This power was fed into the power company network.

Shortly after the Smith-Putnam system had undergone its initial checkout and was brought on line, a main bearing failed. Since World War II was in progress and this project had low priority, it took several years to obtain a new main bearing. The new bearing was installed early in 1945. Following the installation the wind turbine was operated for only a few months when an overstressed blade failed. Total intermittent running time achieved was 1100 hours. The project was reviewed and, although considered to have been a technical success, was not considered to have been an economic success. The original installation cost data indicated that additional machines in small quantities would have cost approximately $190 per kilowatt. The target price in 1945 was $125 per kilowatt. The project was stopped and the wind turbine was dismantled.

The technical results of the Smith-Putnam wind turbine caused Percy H. Thomas, an engineer with the Federal Power Commission, to spend approximately 10 years in a detailed analysis of wind power generation of electricity (refs. 10,11). Thomas, using largely the economic data from

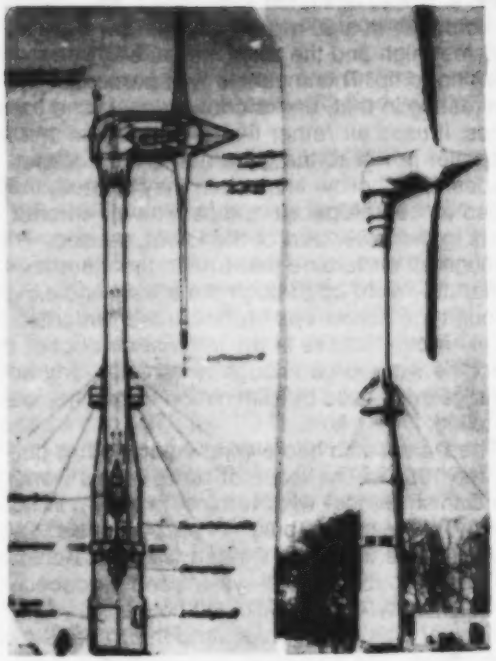

Figure 6. - 100-Kilowatt Enfield-Andreau wind turbine.

Figure 5. - Proposed 6500-kilowatt Percy Thomas twin-wheel wind turbine.

the Grandpa's Knob operation, initially concluded that a 5000- to 10,000-kilowatt wind-driven machine was necessary for economic feasibility. He designed two large machines, one for 6500 kilowatts and the other for 7500 kilowatts.

The 6500-kilowatt machine is shown in figure 5. In 1951 the Federal Power Commission tried to interest Congress in funding a prototype of this machine. Because the Korean War was in progress, the project was not funded and was subsequently canceled. Some details of the proposed system were as follows: The tower height was to be 475 feet, with each of the rotors 200 feet in diameter. The rotors were to drive direct-current generators that would produce 6500 kilowatts at wind speeds greater than 28 mph. The dc power was to feed to a dc-to-ac synchronous converter that would supply the electrical network. All generating equipment was to be housed at the top of the tower. Thomas estimated the capital costs for this machine as $75 per kilowatt.

The English also had a fairly extensive wind energy program from 1945 to 1960 (ref. 7). One machine, shown in figure 6, was the Enfield-Andreau wind turbine. This machine was built in England and set up at St. Albans in the early

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1950's. It was designed to put out 100 kilowatts of ac power in a 30-mph wind. The tower was 100 feet high and the rotor measured 79 feet from tip to tip. This machine was particularly interesting in that, unlike conventional wind turbines, it used air rather than gears to transmit the propeller power to the generator. The propeller blades were hollow and, when they rotated, they acted as centrifugal air pumps. The air entered ports in the lower part of the tower, passed through an air turbine that turned the electric generator, went up through the tower, and exited through the hollow tips of the blades. Unfortunately friction losses in the internal air duct of the machine were large enough to minimize any advantages achieved by elimination of mechanical coupling.

The Danes also had a wind energy effort during the 1950's. The result of some of this work, the Danish Gedser wind turbine, is shown in figure 7. This machine, built in 1957, produced 200 kilowatts in a 33.6-mph wind. It was connected to the Danish public power system and produced approximately 400,000 kilowatt-hours per year. The tower was 85 feet high, and the rotor 79 feet in diameter. The generator was located in the housing on the top of the tower. The installation

Figure 7. - 200-Kilowatt Danish Gedser wind turbine.

Figure 8. - 130-Kilowatt Electricite de France Neyrpic machine.

cost of this system was approximately $205 per kilowatt. This wind turbine ran until 1968, when it was stopped because the power produced was not cost competitive.

The French also did some wind energy work during the 1950's (refs. 7, 12). They built at least two large machines. One machine (fig. 8), with an output of 130 kilowatts, had a blade diameter of approximately 70 feet; the other (fig. 9), with an output of 300 kilowatts, had a blade diameter approximately 100 feet and was located at Nogent Le Roi.

The Germans, under the direction of Dr. Ulrich Hutter, did some very fine work in the 1950's and 1960's (ref. 7). The first machine shown in figure 10 produced 100 kilowatts of power in an 18-mph wind. Previous machines required much higher wind speeds. This machine used lightweight, 115-foot-diameter fiber-glass blades and a simple hollow-pipe tower supported by guy wires. The blade pitch could be changed at higher wind speeds to keep the propeller rotation constant. Hutter's machine ran from September 1957 to August 1968. During this period, he obtained more than 4000 hours of full-rated power operation. He also made substantial contributions to the design of high-speed wind turbine rotors. The

Figure 9. - 300-Kilowatt wind turbine located at Nogent Le Roi, France.

German effort constituted the most advanced work on large wind machines.

Although wind turbine systems have been built and tested in a number of countries around the world, these systems have been dismantled after running for a while. The problem has been that the installation cost per kilowatt has been too high when compared with the cost of other methods of producing electric power. In addition, because of wind variability, it is usually not sufficient to have a wind turbine alone; some form of energy storage must also be considered.

Today's increasing cost of fuel coupled with potential fuel scarcities has caused the reexamination of wind energy as a future source of power. In this regard the Department of Energy (DOE) is responsible for carrying out the Nation's solar energy program, a part of which is wind energy.

Wind energy is being considered because

(1) It is nondepleting.

(2) It is nonpolluting.

(3) The wind is free.

These advantages must be weighed against the disadvantages:

(1) The wind is a variable source.

(2) System costs have been high.

The wind energy part of the National solar energy program (ref. 5) calls for

(1) Studies, construction, and testing of wind energy conversion systems with and without storage

(2) Studies, construction, and testing of energy storage systems

(3) Meteorological studies to estimate the wind energy in the Nation and to determine favorable regions and sites for wind-driven energy systems

(4) Studies and identification of suitable applications for wind energy demonstration tests

The Federal Wind Energy program was initiated in 1973 as a part of the Nation's solar energy program. The first wind energy workshop was held in 1973 (ref. 7) to review past work in wind energy and to assess the potential of wind power. From this workshop it became evident that it was desirable to test a representative large wind turbine as quickly as possible to provide engineering data for use as a base for the entire wind energy program. This wind energy program included the 1973 workshop recommendation to proceed with the design, building, and testing of a

Figure 10. - 100- and 10-Kilowatt German (Ulrich Hutter) turbines.

Figure 11. - Mod-0 wind turbine at Plum Brook.

nominal 100-kilowatt, 125-foot-diameter-rotor wind turbine; this wind turbine was designated Mod-0.

The NASA Lewis Research Center was delegated the responsibility for designing, building, and testing the Mod-0 wind turbine. The Mod-0 became operational in September 1975. Lewis has continued to manage the Mod-0 project and several other large wind turbine projects. These other projects include four 200-kilowatt wind turbines similar to Mod-0 and designated Mod-0A; one 200-foot-diameter, 2000-kilowatt wind turbine designated Mod-1; and several 300-foot-diameter, 2500-kilowatt wind turbines designated Mod-2.

Mod-0 (100 kW) Testbed Project

The Mod-0 wind turbine has been described in a number of reports (refs. 10–21). Figure 11 shows the Mod-0 in operation at the NASA Plum Brook Station near Sandusky, Ohio. This wind turbine has a two-blade, constant-40-rpm, 125-foot-diameter rotor located downwind of the tower. The rotor drives a 100-kilowatt synchronous alternator through a step-up gearbox. The drive train and rotor are located in a nacelle with a centerline 100 feet above ground. The nacelle sits on top of a four-legged steel truss tower. Wind direction is sensed by a wind vane on top of the nacelle and is used as a signal for the yaw control that keeps the wind turbine alined in the direction of the wind. Details of the drive-train and yaw systems are shown in figure 12.

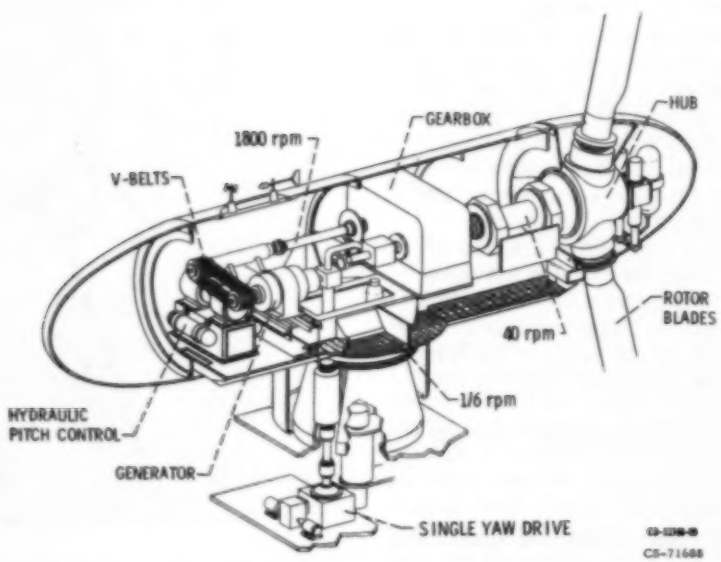


Figure 12. - Tower-mounted equipment for 100-kilowatt wind turbine.

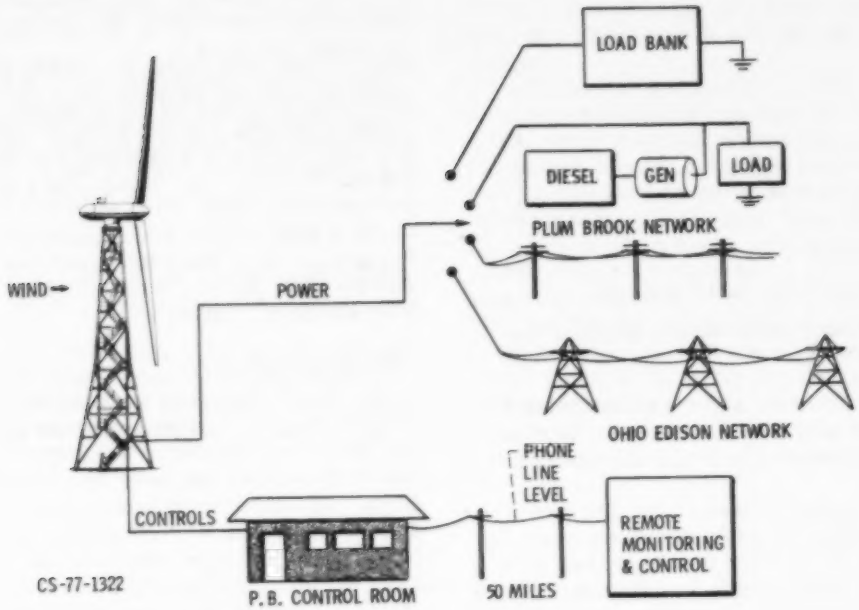


Figure 13. - Mod-0 operation.

The operation of the Mod-0 wind turbine consists primarily of startup, normal operations connected to the utility network, shutdown, and standby. Figure 13 shows the several different modes in which the Plum Brook Mod-0 can be operated. The Mod-0 can be connected to a load bank, to a diesel generator of approximately 160 kilowatts capacity, to the Plum Brook network, or to the Ohio Edison utility grid. The Plum Brook network can be disconnected from the Ohio Edison grid to provide a good simulation of a small utility network with several small generators and real load characteristics. The basic wind turbine controls are shown in figure 14; these are the yaw control for alining the wind turbine with the wind direction and the blade pitch control for startup, shutdown, and power control.

All normal operating functions are programmed into a microprocessor that provides the supervisory control for the wind turbine. A safety shutdown system is wired into the Mod-0 controls to shut the wind turbine down automatically and safely in the event any key parameters are out of tolerance. In addition to the on-site microprocessor and the safety system, a remote control-and-monitoring system allows the Wind Energy Project Office (or a local utility dispatcher in the case of follow-on wind turbines) to monitor and control the wind turbine operation.

When the wind turbine is shut down, the blades are feathered and are free to rotate slowly. The normal wind turbine operation for cutin, rated, and cutout wind speeds is shown in figure 15. For wind speed at cutin (7 mph) or greater the yaw control is activated and the wind turbine is alined with the wind. The blades are then pitched at a programmed rate, and the rotor speed is brought to about 41 rpm. At this time the automatic syn-

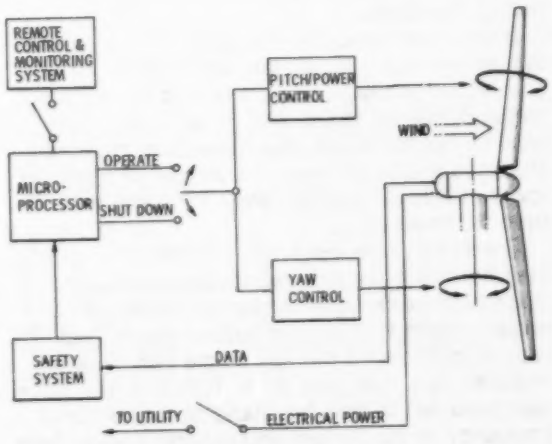


Figure 14. - Mod-0 controls.

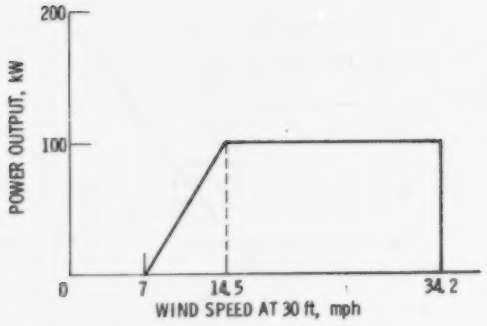


Figure 15. - Mod-0 power output as function of wind speed.

chronizer is activated, and the wind turbine is synchronized with the utility network. Synchronization analyses for the Mod-0 are reported in reference 17.

For wind speeds between cutin and rated (14.5 mph) the blade pitch angle is held constant. For wind speeds above rated the blade pitch is automatically controlled to limit the wind turbine power to 100 kilowatts. For wind speeds above cutout (34 mph) the blades are feathered and the wind turbine is shut down. All these wind speeds are measured at a 30-foot elevation.

The Mod-0 first achieved rated speed and power in December 1975. At this time the machine performed as predicted except for the larger-than-expected blade bending moment (ref. 18).

These blade loads were higher than expected for both the flat (out of plane) and edge (in plane) moment loads. As a result of the high blade loads, an intensive study was undertaken to analyze the load data, to determine the causes of the high loads, and to recommend modifications to reduce the loads.

It was concluded that the tower was blocking the airflow much more than had been expected. The higher blockage was confirmed by site wind measurements (ref. 20) and model tests of the wind tunnel tower (ref. 21). To reduce the tower blockage and to increase the airflow through the tower, it was decided to remove the stairway from the tower.

The study of the edge blade loads, particularly their harmonic content, led to the conclusion that these high loads were caused by excessive nacelle yawing motion. To reduce these loads, it was recommended that the single yaw drive be replaced by a dual yaw drive. This dual yaw drive was expected to help by changing the torsional frequency of the system and moving it away from the 2P (two cycles per rotor revolution) resonance and by eliminating the free play present in the single yaw drive.

As a result of these modifications both flat and edge bending moments were reduced below the values predicted. The problems of tower shadow and yaw stiffness are excellent examples of why the Mod-0 project was begun. The early higher-than-expected loads led to extensive reevaluation of the analytical tools and subsequent redesign of the wind turbine. This information has been extremely important in the design of the large follow-on wind turbines.

Operations Summary

The Mod-0 operations to date have shown that the wind turbine controls for speed, power, and yaw work very satisfactorily. Synchronization to the utility network has been demonstrated routinely. The normal wind turbine operations for startup, utility operation, shutdown, and standby have all been demonstrated and performance is quite satisfactory. The Mod-0 has been used to check out remote operation, as is planned for the Mod-0A and Mod-1 wind turbines. In summary, the Mod-0 has exhibited quite satisfactory operation and no operations problems are apparent at this time.

Major Tests Planned

Several major tests are being planned for the Mod-0. These are primarily tests of various concepts that appear to offer ways of reducing system weight, loads, and complexity and thereby lowering the costs of large wind turbines. The tests presently planned include the following:

Passive yaw.—The yaw drive on the Mod-0 will be decoupled to determine the effects on stability, performance, and dynamic loads. Lower yaw stiffness could result in lighter weight towers and bedplate structure and in lower cost yaw controls.

Upwind rotor.—Analysis has indicated that blade cyclic loads are reduced with the rotor in the upwind direction. The Mod-0 will be modified to allow upwind testing.

Blade tip control.—It appears that rotor power can be controlled effectively by controlling only a small portion of the blade (~15 percent). Such control should result in simpler and less expensive hub and pitch control systems. Tests with tip-controlled blades are planned for the Mod-0.

Teetered hub.—Analysis has shown that the use of a teetered hub reduces the blade flap loads and the yaw loads. A teetered-hub test is

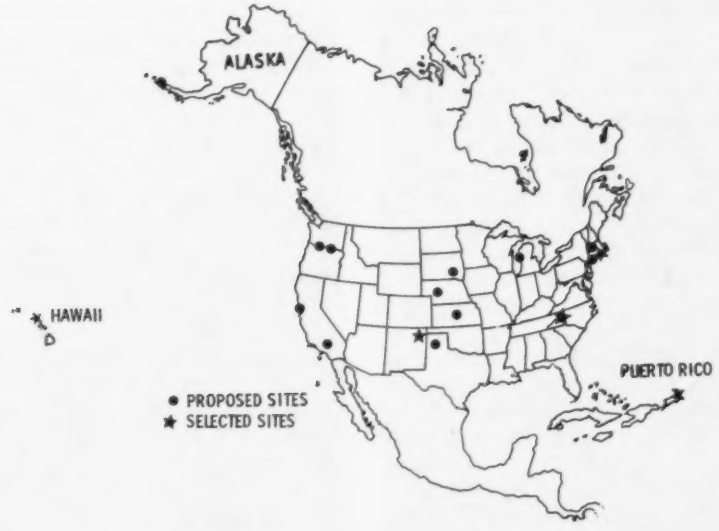
planned for the Mod-0 to verify these analysis results experimentally.

Nonrigid tower.—Analysis has indicated that stable operation can be obtained with nonrigid towers. Such towers will be lighter in weight and lower in cost. Tests to simulate less rigid towers are planned for the Mod-0 in order to obtain data to verify the analysis.

Large Experimental Wind Turbines For Electric Utility Applications

As a part of the Federal Wind Energy program several large experimental wind turbines are being tested at selected utility sites. These large experimental wind turbines include four of the Mod-0A (200 kW) type, one Mod-1 (2000 kW) type, and possibly several of the Mod-2 (2500 kW) designs.

Utility company sites for experimental wind turbines were selected on the basis of proposals submitted by the utility companies. Over 64 utility companies submitted detailed information about their companies and the sites they proposed for installation of wind turbines. These proposed sites were evaluated on the basis of available wind energy, need for supplemental power, interest in supplying personnel for the program, and variations in climatic and topographical conditions. The proposed sites and the sites selected are shown in figure 16, along with the participating utility companies.



SITE	ORGANIZATION	SITE	ORGANIZATION
COLD BAY, ALASKA	ALASKA BUSSELL ELECTRIC CO.	MONTAUK POINT, LONG ISLAND, NEW YORK	LONG ISLAND LIGHTING CO.
POINT ARENA, CALIFORNIA	PACIFIC GAS AND ELECTRIC CO.	BOONE, NORTH CAROLINA[b]	BLUE RIDGE ELECTRICAL MEMBERSHIP CORP.
SAN GORGONIO PASS, CALIFORNIA	SOUTHERN CALIFORNIA EDISON	BOARDMAN, OREGON	PORTLAND GENERAL ELECTRIC CO.
KAHUKA, OAHU, HAWAII[a]	HAWAIIAN ELECTRIC CO.	ISLAND OF CULEBRA, PUERTO RICO[a]	PUERTO RICO WATER RESOURCES AUTHORITY
RUSSELL, KANSAS	CITY OF RUSSELL, KANSAS	BLOCK ISLAND, RHODE ISLAND[a]	BLOCK ISLAND POWER CO.
HOLYOKE, MASSACHUSETTS	CITY OF HOLYOKE GAS AND ELECTRIC DEPARTMENT	HURON, SOUTH DAKOTA	EAST RIVER POWER COOPERATIVE
LUDINGTON, MICHIGAN	CONSUMERS POWER CO.	AMARILLO, TEXAS	SOUTHWESTERN PUBLIC SERVICE CO.
KINGSLEY DAM, NEBRASKA	CENTRAL NEBRASKA PUBLIC POWER AND IRRIGATION DISTRICT	AUGSPURGER MOUNTAIN, WASHINGTON	BONNEVILLE POWER ADMINISTRATION
CLAYTON, NEW MEXICO[a]	TOWN OF CLAYTON		

[a]FOUR SITES SELECTED FOR 200-kW SYSTEMS.
[b]SITE SELECTED FOR FUTURE INSTALLATION OF 2000-kW SYSTEM.

Figure 16. - Proposed wind turbine sites.

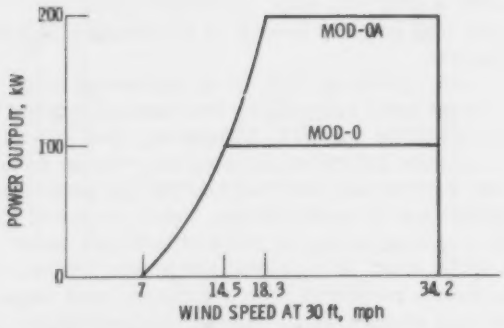


Figure 17. - Power output as function of wind speed for Mod-0 and Mod-0A wind turbines.

Mod-0A Project

The Mod-0A project was initiated in 1975 for the purpose of obtaining early experience with large wind turbines operating on utility networks.

The Mod-0A wind turbine is very similar to the Mod-0 (ref. 16). The major difference is that the gearbox and generator have been increased in size and capacity to provide a power output of 200 kilowatts instead of 100 kilowatts. The 200 kilowatts is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. The rated wind speed is defined as the lowest wind speed at which full power is achieved. The power output as a function of wind speed, shown in figure 17, is regulated by varying the pitch angle of the blades.

The first three sites selected for the 200-kilowatt wind turbine were Clayton, New Mexico; the Island of Culebra, Puerto Rico; and Block Island, Rhode Island, as shown in figure 18. Both the Clayton and Block Island utility companies are isolated and have no tie with neighboring grids, and both companies use diesel- or natural-gas-fueled reciprocating engines to drive their generators. The peak power demands for the Clayton and Block Island utilities are 3000 and 1500 kilowatts, respectively. Culebra just recently installed an underwater cable to bring power from the mainland. Before this, the utility used diesel-powered generators to provide the 800-kilowatt peak power demand. These diesel units are now used as a backup.

The fourth site selected for a 200-kilowatt wind turbine was Kahuka, Hawaii.

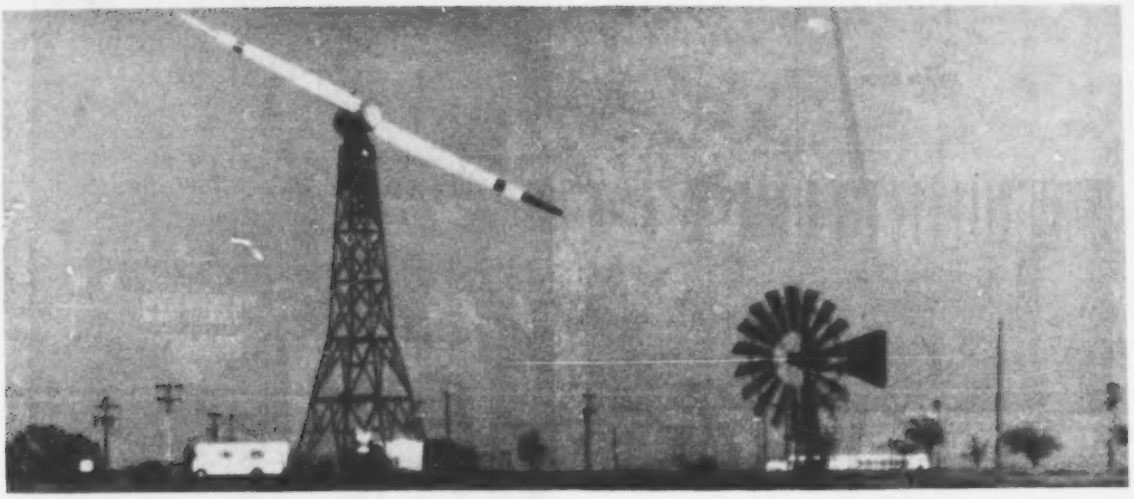
The Clayton wind turbine began operation in early 1978. As of August 1979 the machine had generated 431 megawatt-hours of electricity for the town of Clayton. The Culebra wind turbine began operation in January 1979. The Block Island wind turbine was completed in August 1979. The Kahuka wind turbine is scheduled to start operation in mid-1980.

Operation.—The rated power output of the Mod-0A wind turbine (200 kW) is achieved at a turbine rotor speed of 40 rpm and a rated wind speed of 18.3 mph. The power output as a function of wind speed, shown in figure 17, is regulated by varying the pitch angle of the blades. At wind speeds below cutin and above cutout the rotor blades are placed in a feathered position and no power is produced. The cutin wind speed, defined as the lowest wind speed at which power can be generated, is 6.9 mph. The cutout wind speed, defined as the lowest wind speed at which wind turbine operation would result in excessive blade stress, is 34.2 mph.

Mechanical systems.—The 200-kilowatt wind turbine system, shown schematically in figure 19, consists of the turbine rotor and nacelle, the tower, the hoist, and the control building. The two propeller-like rotor blades, which rotate about a horizontal axis, are located downstream of the tower. The drive-train assembly, which converts the 40-rpm rotor speed to the 1800-rpm generator speed, is enclosed in a fiber-glass nacelle for protection from the environment. The rotor-nacelle assembly is positioned at the top of a tower to provide the necessary blade-tip-to-ground clearance. The hoist provides access to the equipment mounted at the top of the tower. The onsite controls and electrical switchgear are housed in the control building at the base of the tower. A cutaway drawing of the tower-mounted equipment with all major components identified is shown in figure 20. A photograph taken during the shop assembly of the Clayton machine, included as figure 21, shows the relative size and positioning of the various components. The primary design specifications and operation parameters are summarized in table I. Some of the components are now discussed in detail.

Blades: The rotor blades are made of aluminum, except for the cylindrical blade-root shank, which is made of steel. The blade, shown in figure 22, consists of a main load-carrying spar and ribs covered by a thin sheet-metal skin. The construction is similar to that of a conventional airplane wing.

Hub: The rotor hub, shown in figure 23, connects the blades to the low-speed shaft and houses the pitch-change mechanism. The hub is rigid; that is, the blade is rigidly attached to the hub and is permitted only the pitch-change degree of freedom. The hub transmits the torque developed by the rotor blades to the shaft and



(a) DOE/NASA 200-kW experimental wind turbine in Clayton, New Mexico.

(b) DOE/NASA 200-kW experimental wind turbine at Island of Culebra, Puerto Rico.

(c) DOE/NASA 200-kW experimental wind turbine at Block Island, Rhode Island.

Figure 18. - 200-Kilowatt wind turbines.

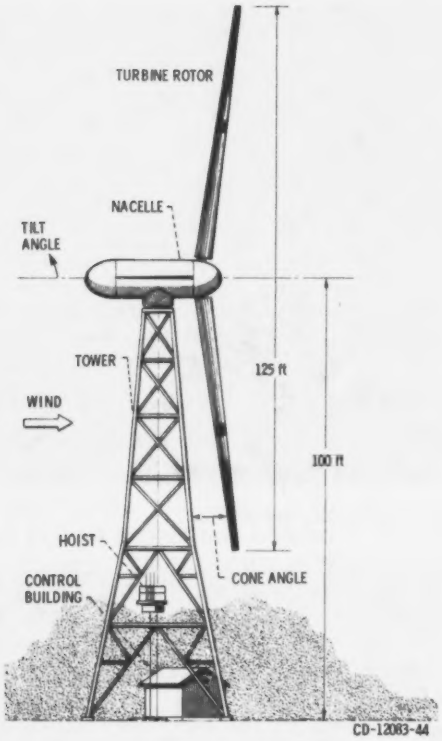


Figure 19. - 200-Kilowatt wind turbine system.

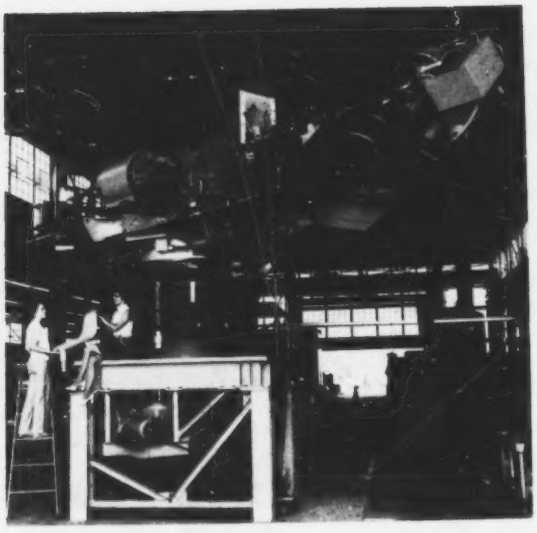


Figure 21. - 200-Kilowatt wind turbine assembly.

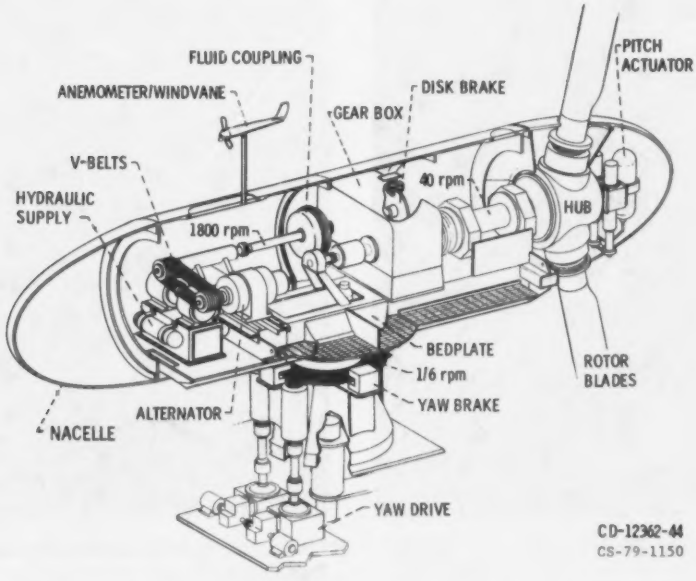


Figure 20. - Tower-mounted equipment for 200-kilowatt wind turbine.

TABLE I. - DESIGN SPECIFICATIONS FOR 200-kW WIND TURBINES

Rotor:	
Number of blades	2
Diameter, ft	125
Speed, rpm	40
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulattion	Variable pitch
Cone angle, deg	7
Tilt angle, deg	0
Blade:	
Length, ft	59.9
Material	Aluminum
Weight, lb/blade	2300
Airfoil	NACA 23000
Twist, deg	26.5
Solidity, percent	3
Tip chord, ft	1.5
Root chord, ft	4
Chord taper	Linear
Tower:	
Type	Pipe truss
Height, ft	93
Ground clearance, ft	37
Hub height, ft	100
Access	Hoist
Transmission:	
Type	Three-stage conventional
Ratio	45:1
Rating, hp	460
Generator:	
Type	Synchronous ac
Rating, kVA	250
Power factor	0.8
Voltage, V	480 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive:	
Type	Ring gear
Yaw rate, rpm	1/6
Yaw drive	Electric motors
Control system:	
Supervisory	Microprocessor
Pitch actuator	Hydraulic
Performance:	
Rated power, kW	200
Wind speed at 30 ft, mph (at hub):	
Cutin	6.9 (9.5)
Rated	18.3 (22.4)
Cutout	34.2 (40)
Maximum design	125 (150)
Weight, lb:	
Rotor (including blades)	12,200
Above tower	44,900
Tower	44,000
Total	88,900
System life:	
All components, yr	30

Figure 22. - Rotor blade.

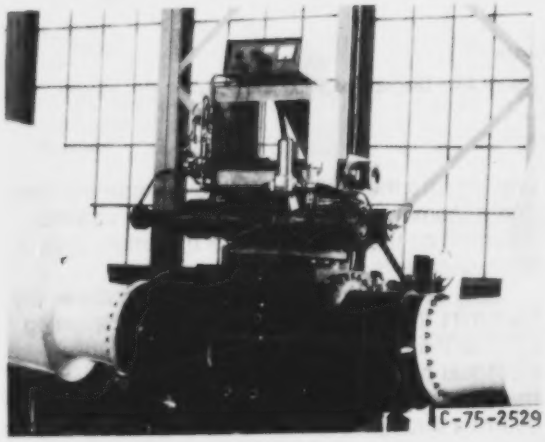


Figure 23. - Hub and pitch-change actuator.

transmits all other blade loads into the bedplate through the low-speed shaft bearings.

Pitch-change assembly: The pitch-change assembly consists of a hydraulic supply, a rack-and-pinion actuator, and gears to rotate the blades in the hub. This type of pitch-change mechanism is similar to that used in the aircraft industry on variable-pitch propellers. As shown in figure 24, a pair of racks is moved linearly back and forth by hydraulic pressure. This pair of racks rotates a pinion that turns a master gear that in turn rotates the blades through bevel gears bolted to the blade spindle. The hydraulic supply is mounted separately inside the front of the nacelle, as shown in figure 20. Hydraulic fluid is

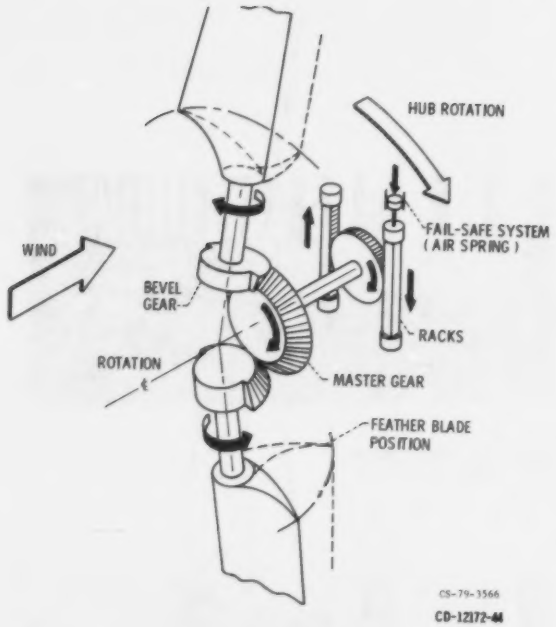


Figure 24. - Diagram of blade pitch-change mechanism.

brought into the main shaft through rotating seals and transmitted to the rack-and-pinion actuator mounted on the rotor hub. The maximum rate of pitch change is 8 degrees per second.

Drive-train assembly: The drive-train assembly transmits the mechanical power of the spinning rotor to the generator, which generates the electrical power, as shown in figure 20. The hub transmits the high-torque–low-speed power to the gearbox through a low-speed shaft. A 1:45 fixed-ratio gearbox transmits this power to the high-speed shaft at low torque and high speed. This power is then transferred to the generator through a belt-and-pulley drive system. The belt-and-pulley drive system offers the flexibility of making small changes in the nominal 40 rpm of the low-speed shaft while still maintaining the constant 1800 rpm required by the generator. If test data show that a higher or lower turbine rotor speed would be desirable, the ratio of the shaft speeds can be changed.

Disk brake: A disk brake system, located on an extension of the high-speed shaft, serves as both a parking brake and a dynamic brake to stop the rotor during an emergency shutdown.

Bedplate: The bedplate is the steel structural member that supports the entire rotor-nacelle assembly.

Yaw assembly: The entire machine on top of the tower is supported on a turntable bearing that permits rotation for proper alinement with the wind. Rotation is achieved by driving a large bull gear with two pinion gears, as shown in figure 20. The two pinion gears, which are preloaded against each other to increase torsional stiffness, are driven by separate motors and yaw drives. If necessary, yaw control can be achieved by using only one unit. The yaw drive, at a rate of 1/6 rpm, is operational whenever the wind speed exceeds the cutin wind speed of the wind turbine.

Yaw brake: The torsional stiffness of the rotating machinery is further increased by activating the three yaw disk brakes shown in figure 20. Even during the yawing motion some brake pressure is applied to damp out any torsional oscillations by maintaining a drag force. Once the machine has alined itself to the wind, this brake pressure is increased to the maximum.

Fluid coupling: The function of the fluid coupling on the high-speed shaft is to damp out the power oscillations resulting from the continuously varying wind velocity that the blades must withstand because of the tower shadow and the wind shear effects.

Figure 25. - DOE/NASA 2000-kilowatt experimental wind turbine at Boone, North Carolina.

Generator: The generator is a commercially available synchronous machine with the specifications given in table I.

Tower: The open-truss tower was built of round pipe members rather than other structural steel shapes in order to maximize the airflow through the tower. The increased airflow through the tower reduces the cyclic stresses on the rotor blades as they pass through the tower wake. The tower is anchored to a concrete-slab foundation.

Hoist: Access to the tower-mounted components is provided by a cable-mounted hoist. This system was selected over conventional stairs to further maximize the airflow through the tower.

Mod-1 (2000 kW) Project

The objective of the Mod-1 wind turbine project is to develop a megawatt-size wind turbine with the potential for generating electrical power on utility systems at costs competitive with those of alternative energy sources. General Electric's Space Division was awarded a contract in July 1976 to design and build a megawatt-size wind turbine optimized for a site with a mean wind speed of 18 mph. Details of this design are presented in reference 24. This wind turbine, shown in figure 25, began operation on Howard's Knob in Boone, North Carolina, in July 1979. The specifications for the 2000-kilowatt turbine are given in table II. The Mod-1 and Mod-0A operating characteristics are compared in figure 26.

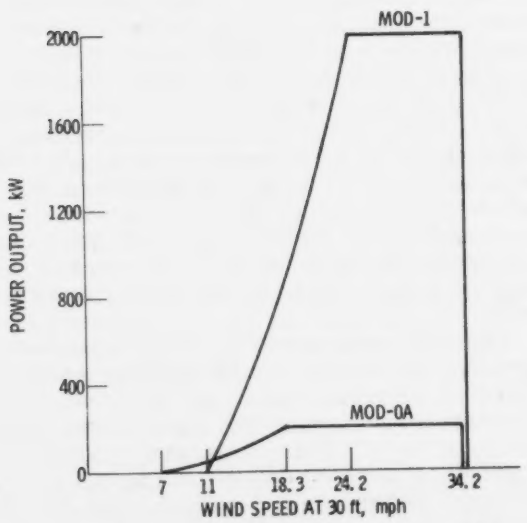


Figure 26. - Power output as function of wind speed for Mod-0A and Mod-1 wind turbines.

TABLE II. - DESIGN SPECIFICATIONS FOR 2000-kW WIND TURBINE

Rotor:	
Number of blades	2
Diameter, ft	200
Speed, rpm	35
Direction of rotation	Counterclockwise (looking upwind)
Location relative to tower	Downwind
Type of hub	Rigid
Method of power regulation	Variable pitch
Cone angle, deg	9
Tilt angle, deg	0
Blade:	
Length, ft	97
Material	Steel spar, foam trailing edge
Weight, lb/blade	21,500
Airfoil	NACA 44XX
Twist, deg	11
Tip chord, ft	2.8
Root chord, ft	12
Chord taper	Linear
Tower:	
Type	Pipe truss
Height, ft	131
Ground clearance, ft	40
Hub height, ft	140
Access	Hoist
Transmission:	
Type	Three-stage conventional
Ratio	51
Rating, hp	2209
Generator:	
Type	Synchronous ac
Rating, kVA	2225
Power factor	0.8
Voltage, V	4160 (three phase)
Speed, rpm	1800
Frequency, Hz	60
Orientation drive:	
Type	Ring gear
Yaw rate, deg/sec	0.25
Yaw drive	Hydraulic
Control system:	
Supervisory	Computer
Pitch actuator	Hydraulic
Performance:	
Rated power, kW	2000
Wind speed at 30 ft, mph:	
Cutin	11
Rated	25.5
Cutout	35
Maximum design	125
Weight, lb:	
Rotor (including blades)	10,300
Above tower	33,000
Tower	32,000
Total	65,000

Figure 27. - Mod-2 wind turbine.

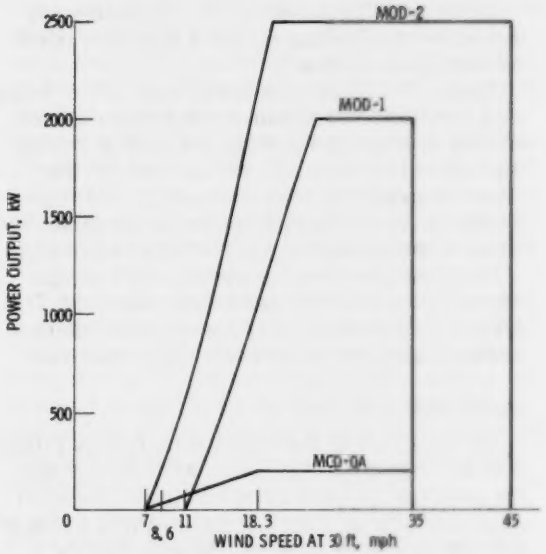


Figure 28. - Power output as function of wind speed for Mod-0A, Mod-1, and Mod-2 wind turbines.

Mod-2 (2500 kW) Project

The objective of the Mod-2 project is to determine the potential cost effectiveness of megawatt-size wind turbines, with rotors of 300 feet in diameter or more, when located at sites with moderate (14 mph mean) winds.

A contract for the design, fabrication, and assembly of three wind turbines was awarded to The Boeing Co. in August 1977. Boeing proposed a two-blade, downwind wind turbine rated at 2500 kilowatts, as shown in figure 27. The estimated power outputs of the Mod-2, Mod-1, and Mod-0A machines as a function of wind speed are compared in figure 28. The Mod-2 has a conventional gearbox and generator, but the whole assembly is mounted on a more flexible tower than the one used in the Mod-0A and Mod-1 designs.

Boeing has been evaluating several primary trade-offs during the initial part of the program. These trade-offs include upwind and downwind rotors, two- or three-blade rotors, teetered and rigid hubs, soft and rigid towers, and a number of different drive-train and power-generation configurations.

The wind turbine proposed by Boeing has conventional welded-steel construction for the blades and towers and is estimated to weigh 625,000 pounds. The first Mod-2 is scheduled to start operation in late 1980. The sites for the Mod-2 wind turbines will be selected this year by DOE.

Current National Program

The goal of rapid commercialization of wind energy intensified planning and analysis efforts as well as development of reliable, cost-effective machines. In fiscal year 1978, the Federal Wind Energy program placed additional emphasis on studies to identify both good potential areas and applications for wind systems and possible legal, social, environmental, and institutional barriers. Applications of wind energy for uses ranging from small and large utilities to water pumping and apple cooling were studied. Techniques and methodologies for identifying sites with good wind resources were assessed, and wind resource data were recorded and analyzed for prospective sites.

Technology development and wind turbine engineering development programs continued, with important advances in small- and large-machine development and testing. The small-machine test facility at the DOE Rocky Flats plant in Golden, Colorado, is gathering data on commercial machine performance and reliability. Data on wind resources, wind systems, and commercial manufacturers of wind energy conversion

systems are available to potential users in recent publications. The Mod-0 experimental 100-kilowatt machine continued to be operated as a testbed for new rotor blades and other turbine components as well as for various configurations in order to provide additional technical information for both present and future generations of large wind turbines.

Recognizing that alternative energy sources may be exploited through radically new and different concepts as well as through established technologies, the Federal Wind Energy program supported investigations of several advanced and innovative systems during fiscal year 1978. Development of the Darrieus vertical-axis wind turbine continued with construction and performance testing of a 17-meter prototype. Other investigations, such as those of a tornado type of turbine and a polarized generator driven directly by the wind, are being supported to assess the potential of unique inventions to fulfill present and future energy requirements.

Mission Analyses and Regional Applications Studies

Economic and market analyses provide program planners, industry, and potential users with vital information and forecasts for large and small systems. A study of economic incentives has provided a basis on which program planners can consider what government action is required to stimulate wind turbine commercialization. The study analyzed the potential impact of such incentives as direct cash subsidies, tax credits, loans, and loan guarantees on wind turbine manufacturers and on utility, residential, agricultural, and industrial users.

Regional applications studies were expanded to include assessment of potential markets in Hawaii and New England. The studies are identifying high potential applications; analyzing costs and cost sensitivity; determining wind resources; and defining the operational, maintenance, and interface requirements related to each application. Results of the studies will provide information about specific regional requirements and applications, as well as a data base for future, expanded large- and small-machine applications studies.

Legal, Social, and Environmental Issues

Studies of the potential environmental, legal, and social impact of wind turbines identify issues that can impede rapid development of the wind energy resource. Field studies conducted by Battelle Memorial Institute of Columbus, Ohio, indicate that an operating wind turbine generator does not pose a high risk to birds and is not likely to have any secondary effects on vegetation, including crops. University of Michigan studies used the prototype Mod-0 wind turbine at the NASA Plum Brook Station near Sandusky, Ohio, to measure the effects of turbine operation on electromagnetic conditions and the biophysical environment. No interference with FM transmission or television audio signals was observed. Video distortion was marked at close ranges and at high frequencies; however, this is a site- and machine-specific problem that will require evaluation for each individual machine and site.

Public acceptance of wind turbine systems will have an important effect on commercialization efforts. To measure public attitudes, a recent study surveyed knowledge of, and reaction to, wind and solar energy generally and wind turbine designs in a variety of settings specifically. Results of the study indicated a positive correlation between knowledge about wind energy and attitudes toward the use, location, and design of wind turbines.

Wind Characteristics

Pacific Northwest Laboratory (PNL) is responsible for the technical direction of the wind characteristics work and for providing the meteorological work and background information that is useful in site determination. Research projects in this field in 1978 focused primarily on the investigation of mesoscale, or large area, techniques; they involved gaining more detailed information on wind regions to provide more information to users. The PNL published "A Handbook of Wind Turbine Siting Techniques Relative to Two-Dimensional Terrain Features" in 1978 as a users manual for utility and civil engineers, city planners, and architects. The study covers general siting practices, hazards, where to find wind power at its maximum, and the optimum site relative to specific terrain features (i.e., bluffs, cliffs, and shelter belts). In a similar effort for small-turbine users, PNL also produced "A Siting Handbook for Small Wind Energy Conversion Systems" for laymen interested in a wind turbine with a power output of less than 100 kilowatts.

Advanced-Systems Research and Development

The Solar Energy Research Institute (SERI) is now responsible for technical management of innovative wind energy systems. Innovative concepts investigated during 1978 included wind augmentation devices such as diffuser and vortex

augmentors; direct-wind-driven systems, which vary from the so-called tornado turbine to charged-aerosol and electrofluid dynamic generators; and the Magnus effect with a Madaras rotor (a reinvestigation). The concepts were investigated both experimentally and analytically, and emphasis was placed on performance and cost effectiveness. Concepts that demonstrate a high potential for successfully meeting these requirements may be supported in field test and demonstration projects.

Small-Systems Test and Development at Rocky Flats

Testing of small commercial wind systems was expanded during fiscal year 1978. Ten systems underwent instrumented, controlled testing; and five more systems have been acquired for tests during 1979. An expansion program, which will increase test-site capacity from 12 sites to 30, is now under way to allow collection of data from additional machines. Long-term goals are to assess performance of small systems, to identify development needs, to assist small-machine manufacturers, and to provide information to potential small-machine users.

Development of Advanced 1-, 8-, and 40-Kilowatt Wind Turbines

The first cycle of contract awards in the small-wind-system test and development program was completed with nine awards for development of systems in the 1-, 8-, and 40-kilowatt size ranges. These competitively selected advanced designs include vertical- and horizontal-axis turbines intended for applications that range from remote communications stations through residential use to large farms or small businesses and factories.

Four of the projects will develop 8-kilowatt systems; three are for high-reliability, minimum-maintenance 1-kilowatt systems (fig. 20); and two projects will develop 40-kilowatt systems. Four of the nine contracts were awarded to small businesses. During fiscal year 1979, contracts will be awarded on other size classes, and the entire small-system effort will be broadened and intensified.

United States Department of Agriculture Programs

The United States Department of Agriculture (USDA) Agricultural Research Service is charged with the responsibility for managing projects to identify requirements for farm and agricultural wind systems. Extensive application studies are in progress. The principal milestones in fiscal year 1978 consisted of wind-powered experiments in water pumping for remote applications, farm building heating, dairy milk cooling, and reverse-osmosis desalination. In addition, alternative techniques for wind-powered irrigation systems and the feasibility of wind-driven brooder heating systems and farrowing pens have been examined. In March 1978 a 40-kilowatt irrigation pumping system was installed at Bushland, Texas, to obtain performance data. The pumping system is powered by a drive system that combines a Darrieus windmill and an internal combustion engine or electric motor.

Summary of Current National Program

Intertie with electrical utilities appears to be the most promising method for generating electricity with wind turbines while assuring uninterrupted electrical service. Future studies will therefore concentrate on important interface questions, including costs, rate structure, and operational and safety factors. Analyses of these problems will provide important data for potential users in planning applications and for manufacturers in product planning.

Economic incentives and demonstration projects to stimulate the use of large and small wind turbines are under consideration. Demonstrations of turbine operation in a variety of applications and environments may be a valuable method for increasing public knowledge about, and acceptance of, wind energy. As reliable, cost-effective machines are developed, such projects will help to identify high-potential applications and to further refine the technology. Economic incentives, including tax benefits and direct subsidies, are being evaluated. Market data will assist program planners in assessing the potential impact of incentives on a variety of markets, including utilities and residential, agricultural, and industrial users.

Through regional applications studies, detailed questions associated with integrating wind turbines into utility networks will be addressed. Analyses of technical and institutional factors relating to particular utility configurations, mixes of existing power-generation equipment, and long-term plans for alternative mixes will provide a data base for long-term planning.

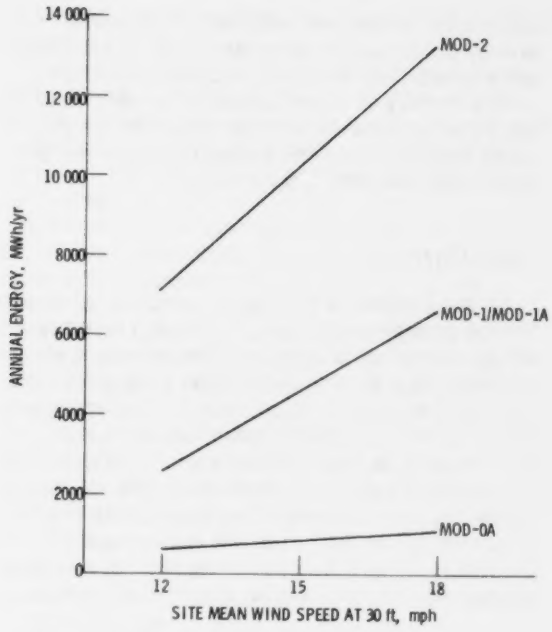


Figure 29. - Annual energy output.

Energy and Cost Comparison

Energy

The annual energy output of large wind turbines is shown in figure 29 for site mean wind speeds from 12 to 18 mph. The energy output was calculated by assuming 90-percent machine availability; that is, it was assumed that the wind turbine will be shut down for maintenance 10 percent of the time that the winds are in the range for generating power. Figure 29 shows the large increase in annual energy that is available as the rotor diameters are increased from 125 to 200 to 300 feet. A Mod-2 at a site with a mean wind speed of 15 mph should produce 10,400 megawatt-hours of electricity a year. This is enough to provide the electrical requirements of approximately 1400 households, assuming that an average household requires 600 kilowatt-hours per month. A Mod-1 and Mod-0A wind turbine at the same site could generate enough electricity for 640 and 120 households, respectively.

Cost of Electricity

The cost of the electricity (COE) provided by a wind turbine is calculated with the following equation:

$$\text{COE (¢/kWh)} = \frac{(\text{Capital cost})(\text{Annual charge rate})}{\text{Annual energy}}$$

The annual charge rate is assumed to be 0.18 and includes the following: (1) capital recovery, (2) state and Federal taxes, and (3) operations and maintenance.

Second-unit costs.—The estimated capital costs for the second Mod-0A, -1, -1A, and -2 wind turbines and the annual energy output at two different mean-wind-speed sites are given in table III. From these capital costs, annual energy outputs, and the preceding equation, the cost of electricity for each machine was calculated (fig. 30). Figure 30 shows that the cost of electricity produced by these large machines at sites with mean wind speeds from 18 down to 15 mph varies from 5 to 7 cents per kilowatt-hour for the Mod-2, from 5 to 8 cents per kilowatt-hour for the Mod-1A, and from 20 to 25 cents per kilowatt-hour for the Mod-0A.

Mature-product costs.—To estimate what the cost of a wind turbine might eventually be in production, it was assumed that wind turbines could be fabricated, assembled, and installed for a cost of $2 to $3 per pound. This is a rather simplistic way to estimate the cost of a mature product, but available data show that many machinery items such as large tractors, power shovels, and steam turbines are fabricated, assembled, and distributed for $2 to $3 per pound. The capital cost range for the Mod-1A and Mod-2 wind turbines was estimated from the $2-to-$3-per-pound assumption and the weights given in table III.

TABLE III. - ESTIMATED SECOND-UNIT COST, WEIGHT, AND ENERGY FOR MOD-0A, MOD-1, AND MOD-2 WIND TURBINES

Wind turbine	Capital cost,[a] dollars	Total weight, lb	Mean wind speed at 30-ft elevation, mph	
			15	18
			Annual energy,[b] MWh	
Mod-0A	1250×10^3	89×10^3	892	1,103
Mod-1	3200	698	4,590	6,703
Mod-1A	2078	320	4,590	6,703
Mod-2	3877	625	10,395	13,293

[a]Estimated for second unit.
[b]Assumes 90-percent machine availability.

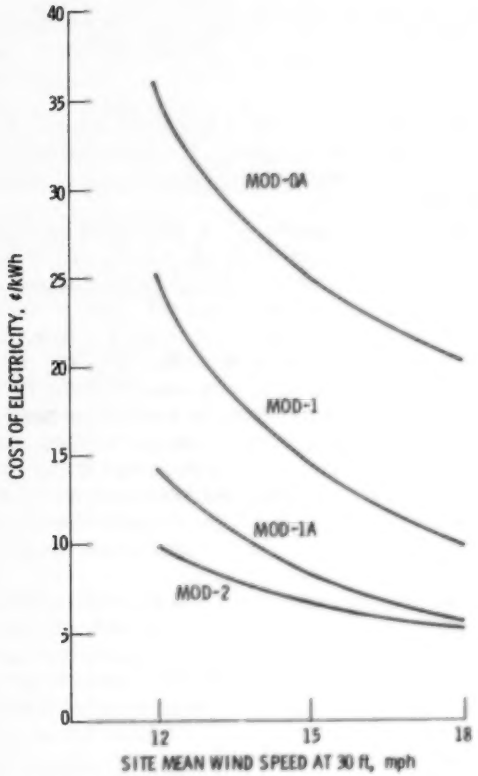


Figure 30. - Estimated cost of electricity for second units. Availability, 90 percent; annual charge rate, 18 percent.

The potential cost of electricity was then calculated from the estimated annual energy for the 12-, 15-, and 18-mph mean-wind-speed sites (fig. 31).

Using this estimation method for obtaining the potential cost of electricity for large, production wind turbines had rather attractive results. Figure 31 shows that the Mod-2 and Mod-1A machines have the potential to generate electricity at 1.7 to 2.5 cents per kilowatt-hour and at 2.2 to 3.3 cents per kilowatt-hour at the 18- and 15-mph mean-wind-speed sites, respectively.

The energy costs for the first Mod-0A and Mod-1 wind turbines vary from 10 to 25 cents per kilowatt-hour for sites with mean annual wind speeds of 18 to 15 mph. A recent redesign of the Mod-1 (Mod-1A) to incorporate design improvements shows that second-unit costs of 5 to 8 cents per kilowatt-hour are possible for these large machines at the 18- to 15-mph sites. Also, the early results of the Mod-2 design studies indicate even slightly lower second-unit costs for electricity. It has been estimated that these energy costs can be reduced to 1.5 to 3.5 cents per kilowatt-hour in a mature-products industry.

In summary, it appears that large wind turbines have the potential to be cost effective in many utility applications if the present designs materialize into mature-product lines.

The Future

As the Federal Wind Energy program advances toward commercialization, increasing emphasis will be placed on studies and development efforts that directly support wind-turbine production and use. Further marketing, economic, and applications studies will identify potential users and provide data to assist industry in planning and development. Studies are now under way to identify areas that demonstrate the greatest potential for wind energy use and to assist in developing strategies to fulfill that potential. Market size and characteristics (e.g., power demand schedule),

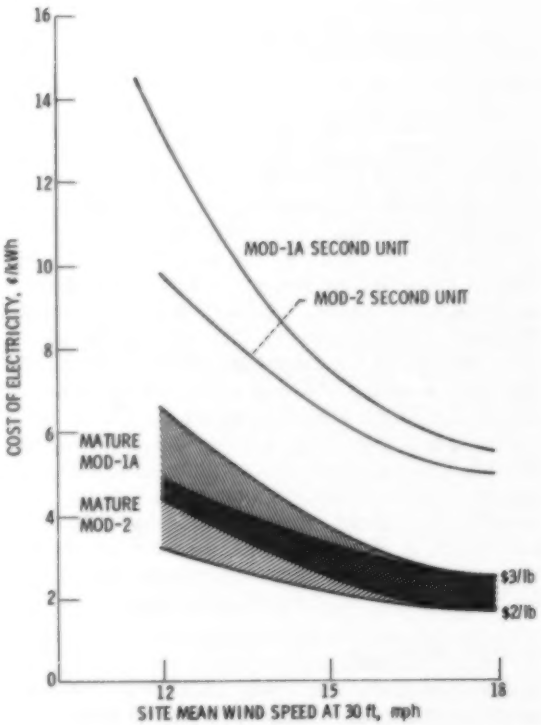


Figure 31. - Estimated cost of electricity for second units and mature products. Availability, 90 percent; annual charge rate, 18 percent.

strategies, sales, and maintenance networks will be analyzed.

The small-machine market will continue to receive strong attention. Although sample utilities will be studied on a regional basis, the results are expected to provide information on classes of problems that can be generalized for application by utilities.

International cooperative efforts will be expanded in the future, and information-sharing programs are expected to enhance program efforts by providing access to alternative technologies and data as well as opportunities to validate analytical techniques. The importance of these programs and international interest in such efforts are likely to increase as a result of the worldwide energy crisis.

Technology development programs will investigate components and systems and the relationship between the wind and the dynamics of the wind system in order to produce lighter, less expensive, and more reliable and efficient machines. This goal will require the development of improved design tools and manufacturing techniques, as well as the development and evaluation of new hardware designs and configurations. Promising concepts and ideas will be tested and evaluated on experimental wind turbines, and electrical interface problems will be explored in anticipation of integrating significant numbers of turbines with conventional power systems. The involvement of numerous commercial manufacturers will be encouraged in an effort to develop expertise and a technology base in the private sector. Technology workshops will be held to present significant new results of the program to the rapidly evolving wind turbine industry.

Large systems will be developed in a cyclical pattern to facilitate transfer of cost, design, and performance information from one generation of machines to the next and to provide a continuous flow of machine development. Second-generation machines are being developed, and third-generation machines are in the planning phase. The small-machine development program will follow a similar cyclical pattern. In addition to the 1-, 8-, and 40-kilowatt machines being developed by nine manufacturers and tested at DOE's Rocky Flats plant, the program will begin additional cycles of small-machine development that will take advantage of design, performance, and cost data derived from the initial cycle and will be based on needs identified in market and application studies.

BIBLIOGRAPHY

This bibliography lists reports generated by the Federal Wind Energy program. Other sources outside the program that contain pertinent additional bibliographical and technical information are also listed.

As specified in the list, most of these reports are available from

National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161

(703) 557-4650

Other reports are available from

Superintendent of Documents
U.S. Government Printing Office
Washington, D.C. 20402

(202) 783-3238

In the few cases where documents are available from other sources, an address is provided with the entry.

Mission Analysis

Summary of Current Cost Estimates of Large Wind Energy Systems. DSE/2521-1, Energy Research and Development Admin., 1977. (NTIS, 64 pp.) Reviews ERDA-sponsored studies that estimate wind turbine costs, summarizes the most pertinent results, and provides a normalized view of the economics of large wind turbines for electric utility applications.

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